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Delivery system performance case study: Wellton-Mohawk irrigation and drainage district, USA

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Abstract. An irrigation district in southwestern Arizona was studied to assess the performance of its water delivery system. Data were obtained through monitoring of lateral canals, examining water order reports and bills, and conducting a diagnostic analysis of the water delivery and on-farm irrigation systems through interviews. A number of differences between official and *de facto* district operating policies were found. These policies had changed over the years and provided far more flexibility and better service than provided by the original official policy. The canal system, which was designed to be operated under upstream control, was found to be operated under a complex mixture of manual upstream and downstream control that resembled dynamic regulation. Farmers made official (recorded) water orders only about half the time. Deliveries usually occurred within one day of the ordered date, as per district policy, with more late deliveries at the tail end of the system during peak water use periods. On average, the district delivered the rate and duration ordered, but average flow rates for individual deliveries were not accurately estimated due to fluctuating flows. The two biggest shortfalls observed were the lack of water measurement records at intermediate points in the system and lack of thorough water accounting. These shortfalls appeared to have had only a minor effect on overall district objectives.

Introduction

The Wellton-Mohawk Irrigation and Drainage District (WMIDD) has long been considered a well operated irrigation project even by United States standards. The WMIDD has a high-quality, fully concrete-lined canal system and a very flexible delivery scheduling process; the on-farm irrigation systems are predominantly high-flow-rate level basins. District farmers have, in general, a high level of net income.

From the monitoring of canals, studying water orders and billing records, and from diagnostic analysis of district and farm operations, an interesting picture of district performance has emerged. Although it is by no means a complete picture, some misunderstandings about the WMIDD's operations have been dispelled, and specific areas of performance have been defined.

This paper presents preliminary findings, defining performance in terms that are, hopefully, relevant both to the WMIDD and to other irrigation districts. A section describing district facilities and organization is followed by brief descriptions of the data that were collected. The next sections describe district processes for water ordering and scheduling, water delivery, and water billing and accounting. For each, intended or designed operations are compared with actual operations and the resulting performance is quantified and discussed.

District overview

The Wellton-Mohawk Irrigation and Drainage District is located along the Gila River in southwestern Arizona, near the city of Yuma. Native Americans are reported to have farmed in the area since before 1700, while irrigation by white settlers dates from the late nineteenth century. The original river diversion schemes were eventually supplanted by pumping from aquifers, which was more dependable. Throughout the early years of development, both types of projects frequently suffered flood damage. Dams on the Gila and Salt rivers eventually brought flooding under control, but by the mid 1930s salt accumulation in the soils was causing farms to be abandoned. Farmers appealed to the U.S. Bureau of Reclamation for help, and after 20 years of negotiations, planning and design, the existing project was constructed.

Colorado River water is now imported into the area, conveyed up the Gila River valley by a large earthen canal. There are 3 lift stations along the district's concrete lined main canal which lift water to a mesa overlooking the valley. There are also several smaller lift stations scattered throughout the valley. From this "upstream" end of the WMIDD, water is delivered to users by gravity though more than 490 km (300 mi) of concrete-lined main and lateral canals. Another 110 km (70 mi) of lined canals collect and carry away drainage from district-operated wells. The district is in a well isolated geographical basin such that all drainage water from the district is pumped.

The lateral canals range in capacity from 3400 to 425 ℓ/s (120 to 15 ft^3/s) and are typically about 5 km (3 mi) long; some have one or more sublaterals. The project was designed to provide a standard farm flow of 425 ℓ/s (15 ft^3/s). Turnouts typically serve 32 to 64 ha (80 to 160 ac) fields, which are divided into large level basins (Dedrick et al. 1982) of 1 to 8 ha (2.5 to 20 ac).

Farmers have concrete-lined ditches to move water from basin to basin. Although siphon tubes are sometimes used, most basins are irrigated through either port outlets, several per basin, or large concrete turnouts, one per basin.

Typical crops are alfalfa, cotton, wheat, lettuce and citrus. About 24,000 ha (59,000 ac) of cropland are irrigated, although the delivery system was designed to serve 30,000 ha (75,000 ac). Overall irrigation diversion to the district is presently about 0.6 ℓ/s/ha.

About 110 landowners comprise the district, and elect its 9-member board of directors. Operations are headed by a Manager whose principal staff consists of a Civil Engineer, a Power and Pumping Superintendent, a Construction and Maintenance Superintendent and a Watermaster. The Watermaster is in charge of water ordering, delivery and accounting. His staff consists of dispatchers, patrolmen and ditchriders. Dispatchers take water orders, control pumping into the district, and relay information to canal operators; patrolmen operate the main canals, and ditchriders operate the laterals. In all, the district employs about 120 people.

Materials and methods

The data upon which WMIDD's performance was assessed comes from three sources. The first was a canal monitoring project (Palmer et al. 1986, 1987 & 1989) that provided detailed measurements of flow rates, water levels and gate positions along two lateral canals. The first monitored lateral was near the upstream end of the district, between the last two main canal lift stations. Its design capacity was 1700 ℓ/s (60 ft^3/s); 10 farm turnouts were monitored. Data on actual deliveries were collected from June 1985 to December 1988. The second monitored canal was at the far end of the district, 69 km (43 mi) downstream of the last lift station. Its design capacity was 2550 ℓ/s (90 ft^3/s) and had a large sublateral; 17 farm turnouts were monitored. Data on actual deliveries were collected from July 1987 to December 1988. Flumes were placed inline near the head and tail ends of both laterals and at all offtakes where feasible, such that nearly complete records of inflow and outflow were obtained.

Measurements were made automatically every 15 min on a continuous basis, using combinations of air bubblers and pressure transducers coupled to microprocessor-controlled data storage devices (Dedrick & Clemmens 1986). Flow rates were measured by sensing water levels upstream of long-throated flumes (Bos et al. 1984). While the sensors had an accuracy of plus or minus one or two millimeters in the lab, field accuracy was estimated at about ± 4 mm. For a typical measurement site, this translates to flow measurements with an accuracy of about ± 10 ℓ/s (0.4 ft^3/s).

The second source of data was the district. The dispatcher provided copies of the reports he assembles from farmers' water orders, which ditchriders use to schedule deliveries. The accounting office provided the records of flow rate and duration used to calculate farmers' water bills. The water order and bill information was for the late summer period of August through October, 1987 and the spring period of February through April, 1988. The engineering office provided the design canal capacities, plans for the canal system and other technical information.

The third source of district performance data was a diagnostic analysis (DA) of the water delivery and on-farm water management systems, conducted in November and December, 1988. Diagnostic analysis (Clyma & Lowdermilk 1988) is a structured team process for accurately assessing the actual performance of a system, in comparison to intended, designed, or perceived performance. Because a wealth of measurements had already been made during the monitoring project, the DA focused on individuals' decision-making processes and the actions taken to achieve district and farm objectives.

Interviews were conducted with district personnel at each organizational level and with farmers and farm irrigators, to extract their understanding of the system and to learn their job activities. Periods of intense discussion by the DA team (an 'analysis and synthesis' process [Clyma & Lowdermilk 1988]) alternated with follow-up interviews until an improved, common understanding of district performance was developed.

Results

The water ordering system

Official policies

Deliveries are made under a restricted-arranged schedule (Replogle & Merriam 1980). Official district policy requires farmers to order water at least four days in advance of the desired delivery date. 'Requests' for delivery earlier than the fourth day after placing an order are to be considered only in emergency and are subject to water availability; an improperly planned order is not considered an emergency. The district may deliver water one day earlier or later than the farmer's preferred date, to facilitate pumping and other operations.

The dispatcher uses a computer to assemble water orders into reports with which the ditchriders plan deliveries. Each day ditchriders are to contact farmers to confirm orders for the next day. Farmers are required to confirm their orders and turnout locations with the dispatcher the day before delivery. Orders may be canceled up to 12 h before the scheduled delivery time.

In addition to specifying frequency of irrigation, the farmer also arranges duration and flow rate. Durations of up to 72 h are allowed, but if there are conflicts among users of a lateral, the Watermaster may allocate time and use on the basis of relative acreage. A single time extension may be requested while an irrigation is occurring, for up to 6 h, if the request is made 3–6 h in advance.

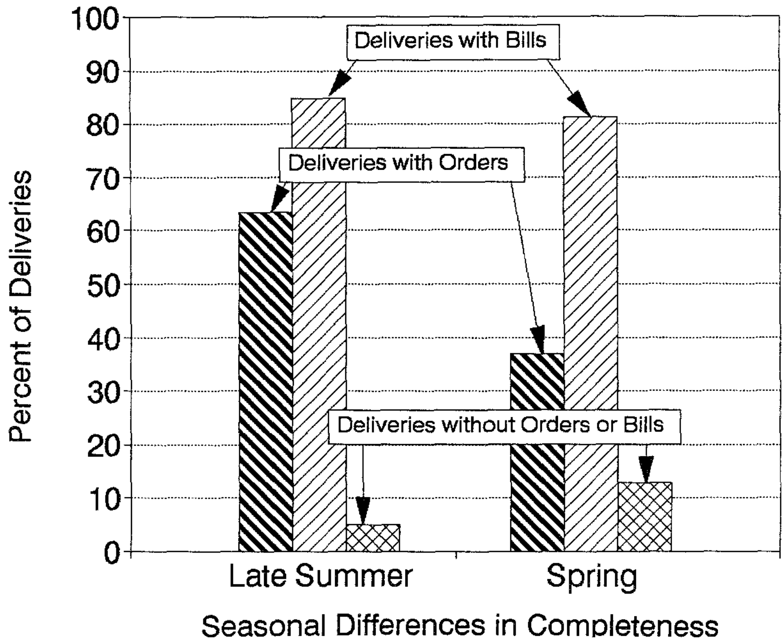

Fig. 1. Portion of measured deliveries with officially recorded orders and those with corresponding bills for both monitored lateral canals, for the late summer period August–October, 1987 and the spring period February–April, 1988.

The rules provide no penalty for inaccurately ordered durations. District policy states that the design turnout flow rate of 425 ℓ/s (15 ft^3/s) should not be exceeded if the canal is thereby endangered or if other water users are affected.

Actual performance

For the purpose of analysis, 'official' orders were considered to be those orders that appeared on the dispatcher's reports, with which the ditchriders schedule water traffic on their respective set of laterals. However, some of the orders listed on those reports were made with fewer than the officially required four days' lead time. Sometimes farmers ordered water which was intended for more than one turnout, and the reports listed the entire volumes of orders as going to a single turnout. In these cases, the orders were split according to the actual durations of corresponding measured events, and assigned to individual turnouts.

Figure 1 is a record of delivery orders and bills for the late summer and spring periods. The portion of deliveries with corresponding official orders was 63.3% for the late summer, and 36.9% for the spring. Overall, 52% of measured deliveries had corresponding official orders.

Figure 2 shows the distribution of ordered, billed, and measured flow rates

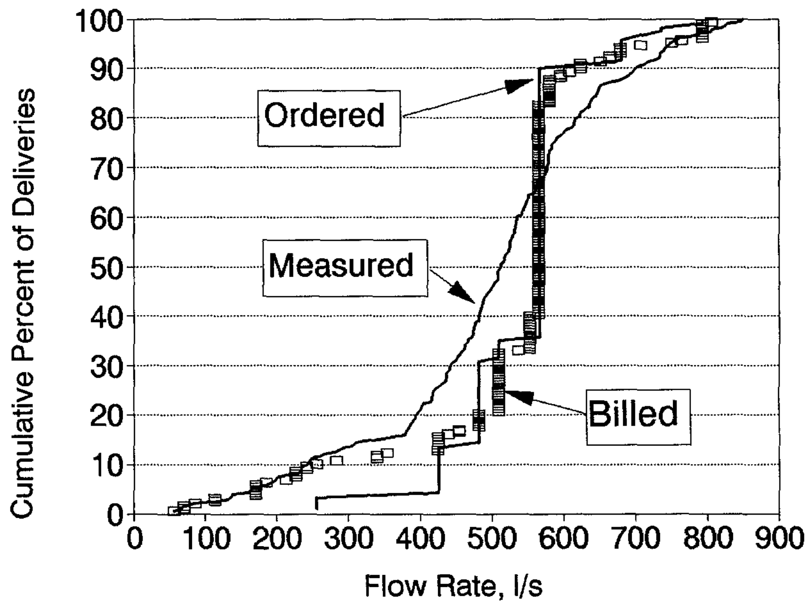

Fig. 2. Distribution of ordered, measured and billed flow rates.

for the two monitored laterals during the same late summer and spring periods. About 13% of the official orders studied were for flow rates equal to or less than the 425 ℓ/s canal design rate. Fifty-five percent (90 minus 35 cumulative percent in Fig. 2) of orders were for 565 ℓ/s, or more than 1.3 times the design value. The mean and median ordered rates were 530 and 565 ℓ/s, respectively. The distribution of ordered flow durations is shown in Fig. 3; the mean and median durations were 17.1 and 11.75 h, respectively.

That farmers were much more likely to make official orders during the late summer than the spring may reflect a greater concern for secure water supplies during this much hotter season, Fig. 1.

DA interviews with ditchriders and the dispatcher indicated that no matter how farmers order water, they frequently negotiate different details of delivery with ditchriders, between the time of the order and the end of the delivery. There are no records of these casual arrangements, but they are probably as important for successful operations as the officially sanctioned process. This represents a high degree of responsiveness to farmer needs which is one reason the district has such a good reputation.

An important factor in WMIDD's responsiveness to changing orders is a well-developed communication system. The district installs and pays for telephones in ditchriders' homes, and two-way radios in their trucks; farmers all have telephones and many have two-way radios. When they are on duty, ditch-

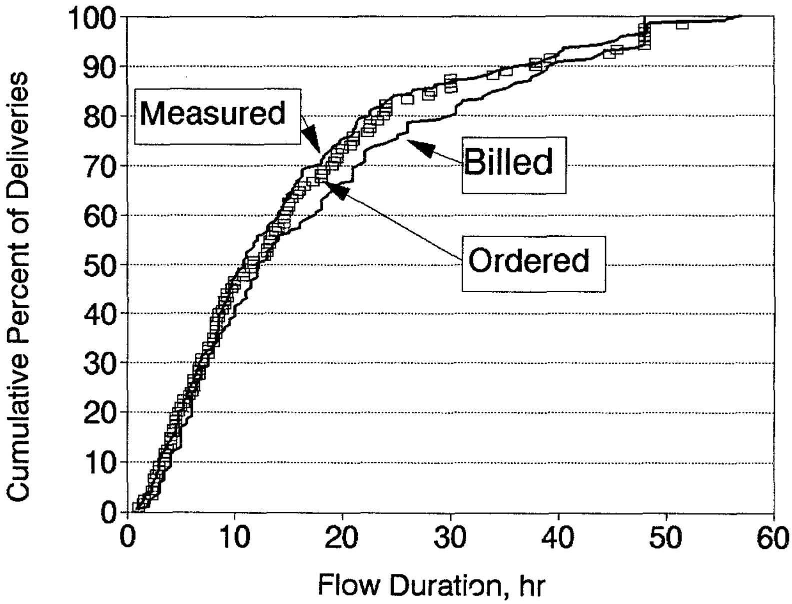

Fig. 3. Distribution of ordered, measured and billed flow durations.

riders are required to be within hearing distance of their telephone or radio at all times.

A major reason for the preponderance of orders for flow rates greater than the design standard is that farm systems were redesigned and rebuilt in the 1970s and early 1980s, as part of a government-sponsored on-farm irrigation system improvement program. These new systems have larger level basins, and typically require larger flow rates for similar efficiencies and distribution uniformities. Farmers' decisions about appropriate flow rates are apparently quite uniform and stable over time, as shown by more than half of all orders specifying the same rate.

The water delivery system

Official policy and original design

WMIDD moves water into the district with manually controlled canal lift stations that are operated remotely by the dispatcher at district headquarters. Flows are distributed through the system with manually operated check structure consisting of gates and weirs. Most farm turnouts are circular sluice gates installed flush with the sideslope of the canal; the remainder are constant head orifices (CHOs). The pumps and gates have been rated and the rating tables collected into a manual for canal operators.

The network was designed to be operated under manual upstream control. The objective of this strategy is to control water levels immediately upstream of check structures and thereby control flow rates through turnouts. Under upstream control a significant lead time can be required to match inflow with demand, and once flow is released from the supply it must pass through the system. In the WMIDD, travel time for water routed from the Colorado River through the system can exceed four days.

Ditchriders are required to call in a water report to the dispatcher each morning and evening, giving delivery locations and flow rates. With this information the dispatcher plans the water traffic pattern on the main canals. The dispatcher checks canal capacities and maintains water balance records. He is responsible for maintaining water levels at the check structures by monitoring a control panel and communicating with the patrolman who drives along the main canals and makes appropriate gate adjustments.

The district has nine ditchrider divisions, each with an average of about seven laterals. Ditchriders are 'on call' 24 h per day and work a schedule of six days on, two days off. Schedules are staggered so that three relief ditchriders can operate the laterals when the regular men are off duty. Two vacation ditchriders operate canals when needed and otherwise are employed as general labor.

Official policy requires ditchriders to measure farm flow by one of three methods: volume meter reading; propeller meter reading; or, at turnouts with CHOs, water level measurements converted to flow rate with a rating table. Other district employees, called hydrographers, are to make independent measurements of flow for comparison with ditchrider flow records.

Actual performance

The district has evolved a canal control process which resembles dynamic regulation (Rogier et al. 1987), where excess water is put into the system to allow for pure demand with no lead-time restrictions. A certain amount of water is pumped into the system based on expected demand, and is handled by upstream control. In DA interviews, the Watermaster said that the system is generally flowing with about 15% more water than has been officially ordered to meet unforeseen demand (district personnel [July 1990] state that this practice has been discontinued). This implies passing the water to the next user immediately when a delivery ends. Further, ditchriders are under strong pressure from district management not to spill water, which is considered a waste.

If late requests for water do not make up for the difference between ordered and actual flow, two options are exercised. Water can be 'backed out' of the laterals with what amounts to manual downstream control, using the capacity of the main canals to store the excesses. Alternatively, ditchriders contact farmers who are typically scheduled to receive water in the next day or two, and ask them to accept their water earlier than ordered. Although the flow rate may not match that ordered, DA interviews indicate farmers usually will accept the early delivery, for which they are billed at regular rates. Water balances for the monitored laterals indicated that very little water was spilled into the wasteways.

In interviews, patrolmen and ditchriders all remarked that limited canal capacities made operations more difficult. They said that the canals carried their design capacity for only a few days after cleaning, and that cleaning did not occur often enough. Ditchriders sometimes increase turnout capacities by raising the level of lateral check structure weirs with pieces of lumber. Often, capacity problems are due to the large flow rates ordered by farmers, which limit the number of deliveries that can occur simultaneously in the smaller laterals.

Ditchriders and patrolmen noted in DA interviews that the operations manuals containing structure ratings and other information did not contain sufficient information for them to perform their duties. Experience operators either added their own personal information to them or did not use them at all. Most claimed they had gained their knowledge of canal operations solely through experience.

Measures of delivery system performance examined are how well the district was able to match the frequency (timing), rate and duration of flow that was intended or desired by the farmers. Each of these variables is examined in turn.

Timeliness. To evaluate whether or not deliveries occurred on-time in comparison to the dates ordered by farmers, timeliness was defined as the days between the ordered and actual delivery dates. Because the official order reports record only the day for which delivery has been ordered, timeliness was calculated on the basis of gross days. For example, if water was ordered for October 10, and delivery began at 11:59 p.m. or earlier on October 9, the timeliness would be +1, or one day early; if delivery began at 12:01 a.m. or later on October 11, the timeliness would be −1, or one day late. Figure 4 shows the results for timeliness calculated this way.

As Fig. 4 shows, 72% of deliveries occurred within the allowed plus or minus one day of the ordered date. The remaining 28% of deliveries were more than one day earlier or later than the ordered date. This analysis does not account for those occasions when farmers and ditchriders negotiate different details of delivery, between the time of the official order and the actual delivery. Along both monitored laterals, the portion of late deliveries was greater during the late summer than during the spring. Deliveries along the downstream lateral during late summer were the least timely, averaging almost 1.5 days late. Upstream lateral deliveries averaged on-time during this period. Later deliveries

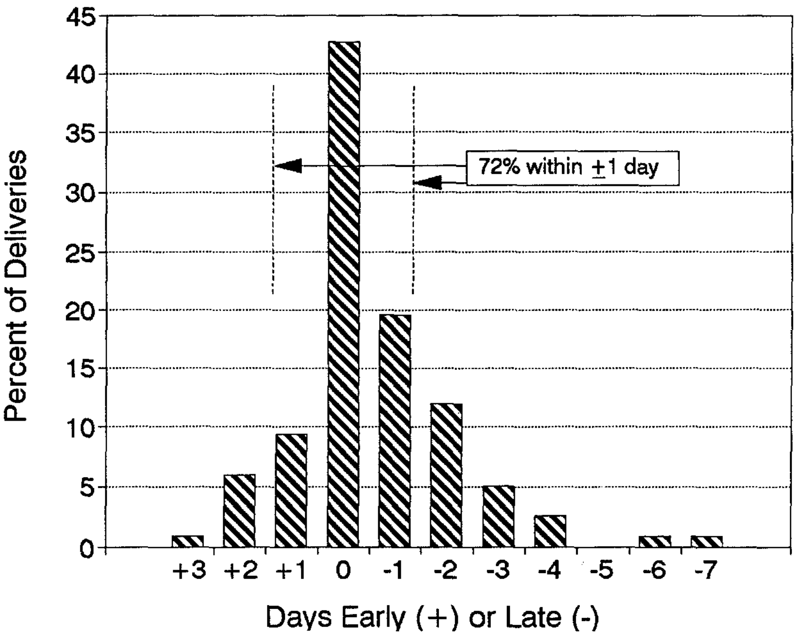

Fig. 4. Timeliness of measured deliveries with corresponding official orders.

for the downstream lateral is consistent with reports on 'tailender' problems in many districts.

At certain times of the year, farmers may recognize an increased possibility of late delivery, and make their orders correspondingly early. As the water orders data show (Fig. 1), farmers are much more consistent making official water orders in the late summer than the spring. But in any case, the accuracy of the timeliness data depends on the extent of informal negotiations between farmers and ditchriders, of which no records are kept.

Flow rate. Figure 2 shows the distribution of measured mean flow rates, which has a wider range than the ordered rates. The average and median measured rates were 498 and 513 ℓ/s, respectively. To study how closely the flow rate and volume provided by the district matched the intent of the farmer, intended flows were assumed to be the same as ordered flows. Adequacy of delivery flow rate is thus defined as the ratio of the average rate actually measured, to the rate ordered by the farmer, or Q_a/Q_0 (Clyma 1988). Figure 5 shows the ranked distribution of adequacy values for those measured deliveries with corresponding official orders.

The mean value for flow rate adequacy was 0.96. This means that, on average, the measured rates were 4% less than ordered. However, there was a wide range in the adequacy of deliveries (Fig. 5). Thirty-three percent of deliveries

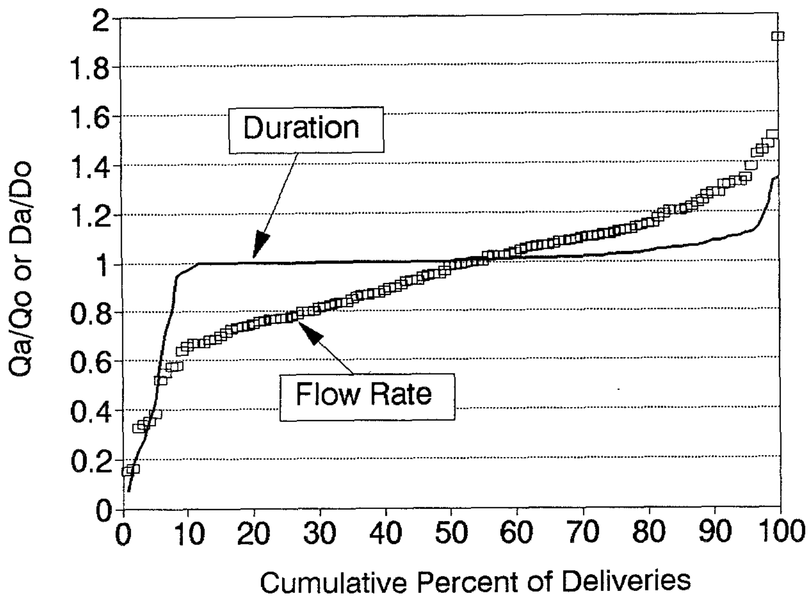

Fig. 5. Distribution of order-based adequacy of delivered flow rates (Q_a/Q_o) and durations (D_a/D_o).

had a mean flow rate that fell within 10% of the ordered rate; 27% had a mean rate more than 1.1 times the ordered rate, and the remaining 40% had a mean rate less than 0.9 times the order.

The distribution of adequacy values indicates that despite the average performance, most deliveries did not accurately reflect farmers' orders. But again, these results depend on the extent of informally negotiated rate changes. Also, one dispatcher interviewed indicated that some farmers simply order water without specifying a rate or duration. Thus what is written down by the dispatcher on the order sheet may not be what the farmer actually intended.

In general, each farm delivery irrigates several level basins in turn, and fluctuations in flow rate can affect the amount of water applied to each basin, complicating the management of the on-farm systems (Palmer et al. 1987). In a study of deliveries on the upstream monitored lateral (Palmer et al. 1989), flow rate uniformity was measured by the coefficient of variation (CV, standard deviation divided by mean) of instantaneous flow rate measurements. A low CV value indicates high uniformity and *vice versa*, as the example delivery hydrographs in Fig. 6 show. Figure 7 shows the variation in flow uniformity for deliveries along the upstream monitored lateral. The mean uniformity was CV = 0.12, the median was CV = 0.08, and the CV was greater than 0.2 for about 12% of the deliveries.

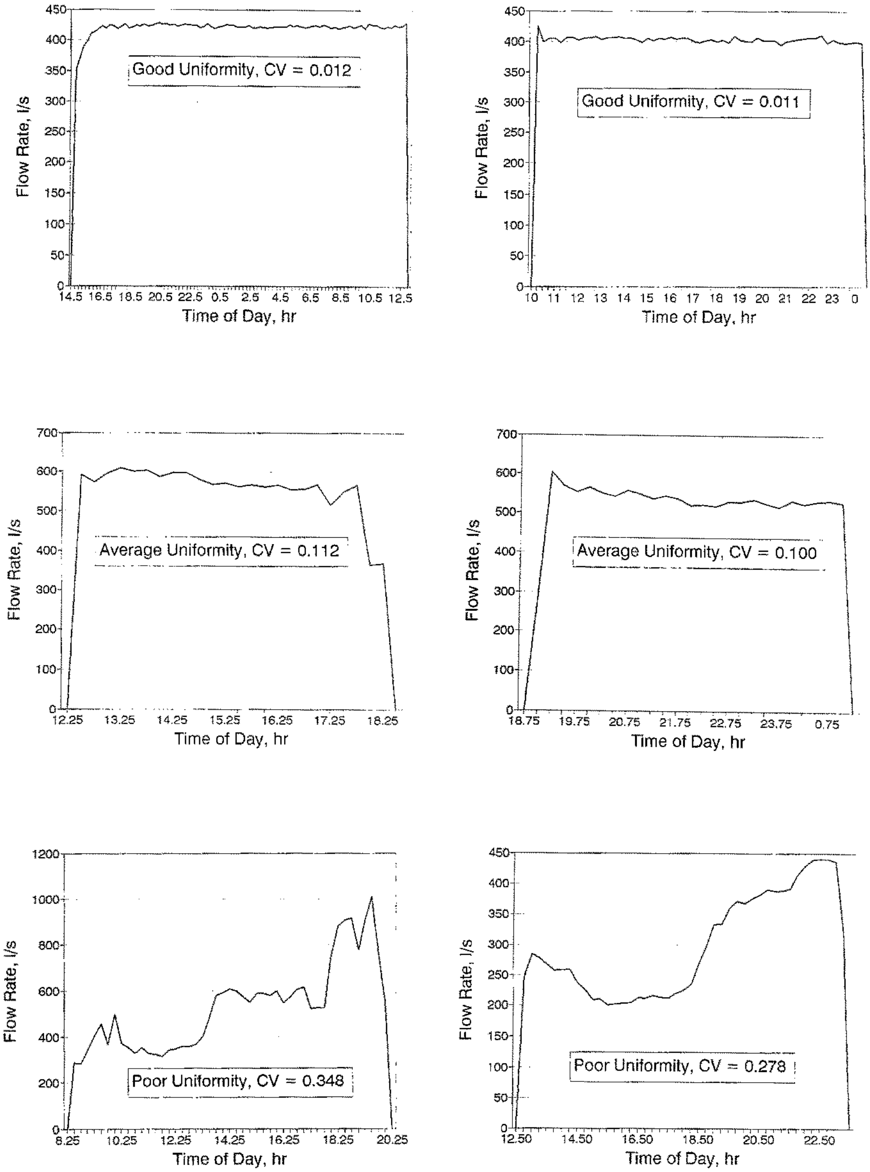

Fig. 6. Example delivery hydrographs of different uniformities.

Palmer et al. (1989) related flow rate fluctuations to a number of individual variables. Uniformity improved with higher mean flow rates and with shorter durations. Flows were much more uniform at turnouts located immediately upstream of a check structure than at turnouts located in the middle of a pool. Uniformity could not be shown to depend on fluctuations in the main canal

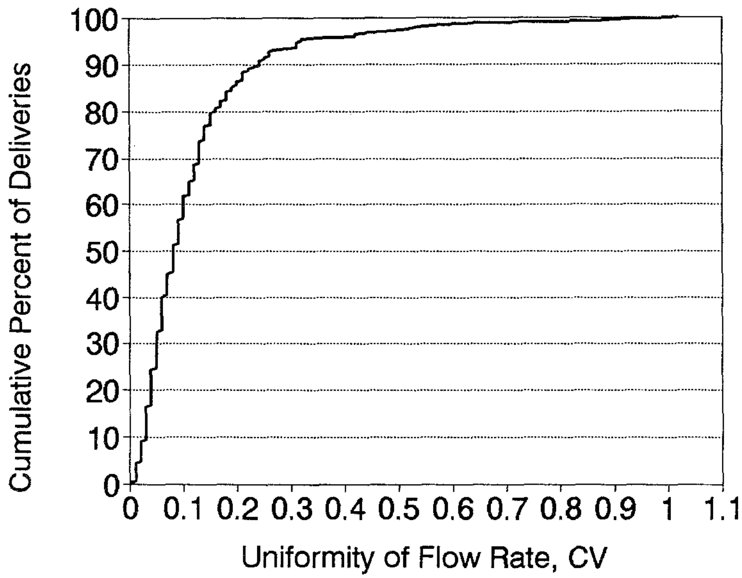

Fig. 7. Distribution of flow rate uniformity values for measured deliveries along the upstream monitored lateral. CV = coefficient of variation = (standard deviation)/(mean).

level, turnout distance from the lateral heading, concurrence with other deliveries, or the time of day or year that the delivery occurred (r^2 values in linear regression analyses very close to zero). While it might be expected that delivery accuracy would suffer under high fluctuations in flow, this was not found to be the case for this data.

Current policy is for the ditchriders to make and record at least two flow measurements at each turnout receiving water per 24-h period. However, many deliveries are shorter than 24 h and only one measurement is made. A majority of turnouts are set up for propeller meter flow measurements. These meters are relatively heavy and unwieldly, and require several minutes to set up, read, and dismantle. Furthermore, under conditions of high flow rates, the propeller meters cannot be reinserted into their stands once flow has been established. Often in practice, the ditchriders use experience to set flows. At lateral headings, they sometimes use the number of turns of the gate stem and water level to estimate flow. At farm turnouts, they use the long-throated flumes (Bos et al. 1984) which were built in nearly all farm ditches at the same time that the on-farm systems were rebuilt. Ditchriders can read the gauges in a few moments, often from the seat of their trucks. Officially, these flumes are not to be used since they are not district owned and maintained. It was discovered during the monitoring project that some farm flume gauges had moved from their original zeroing an read a lower-than-actual flow rate. However, once the ditchrider has compared propeller and flume flow rates he often relies on the flume measurement and adjusts for any differences in flow rate he has observed.

Duration. The DA interviews indicated that farm personnel control the time when the delivery ends. That is, if the time required to complete delivery is shorter or longer than anticipated, the ditchrider must adjust his schedule to accommodate the farmer. Figure 3 shows the distribution of measured durations, which correspond closely with the ordered durations. The average duration was 15.1 h and the median was 10.8 h.

Just as adequacy of delivery was defined for flow rate, duration adequacy can be defined as a measure of how well the actual time of delivery compared to that intended by the farmer, (actual measured duration)/(ordered duration) or D_a/D_o. Figure 5 shows the distribution of duration adequacy; average duration adequacy was 0.98, and the median was 1.00. Seventy-four percent had a measured duration with 5% of the ordered duration.

Farmers appear in most cases to have made accurate estimates of duration. The data on flow rate adequacy implies that farmers in most cases end delivery when planned, regardless of the flow rate received. This finding appears at first glance to conflict with farmers' interviews in which they uniformly stated that they use a spot in the basin which when wetted indicates the time to cut off flow. But the historical performance of a field may be consistent enough that the farmer actually just uses a time that corresponds to water having reached that point in the field during some past irrigation. Alternatively, the farmer may be watching the field regularly, but the time required to reach the point in the basin may not be particularly sensitive to flow rate at the level of variation seen in this system. This process is not fully understood.

The water accounting system

Official policy

Water accounting in the WMIDD begins with measurement into the project at the head of the Wellton-Mohawk canal by the Bureau of Reclamation (who officially distribute water from the Colorado river) and ends with measurements at all farm turnouts and spills from the canal system by the ditchrider. Flow rate measurements at intermediate points are to be made by hydrographers. Drainage flows are also to be measured.

For each delivery made, the ditchrider is to fill out a water card stating the user's name, location, turnout number, beginning date and time, and ending date and time. The card information is transferred to the ditchrider's field book, to make an accurate record of meter readings. The ditchrider fills out a similar card for any water spilled in his division, showing location, time and duration, and reason for the spill. If the ditchrider gives water to a user to avoid spilling to drains, he is to mark the card as a spill but give the user's turnout as the location.

The water cards are sent to district headquarters at the completion of delivery or at the end of 48 h of flow. The district sends bills to farmers each September, with the first half assessment due in December and the second half in June.

Actual performance

Flow rate measurements at the head of the district are made by the Bureau of Reclamation using gate ratings provided by the U.S. Geologic Survey. The canal reach between the heading and the first lift station into the valley is relatively wide and is used to store as well as convey water. It is also unlined and some seepage exists. For operational purposes, the district uses estimates of flow rate by empirical ratings of the pumps at their lift stations. For long term water accounting, these ratings are compared with the Bureau's diversion estimates. District personnel have expressed an interest in obtaining better flow rate measurements at these lift stations.

The district no longer employs hydrographers, so the only flow measurements made downstream from the main canal lift stations are made by ditchriders. Flow rates at the head of lateral canals are not recorded. Drainage flows are measured in pump discharge pipes with totalizing flow meters.

There are provisions in district policy for resolving conflicts with farmers over flow measurements, but these provisions are only invoked if there are complaints from farmers. DA interviews revealed that one of the ways ditchriders act to prevent complaints is to try to provide higher-than-ordered flow rates to the farmers. This is not supported by the measured data which indicates a lower than ordered flow rate on average.

In interviews, the district Engineer and Watermaster said that the district has not been able to account for about 15% of their diversions. District records show that the WMIDD had an average annual conveyance-distribution efficiency (ratio of deliveries to diversions) of 85% for the period 1981–1986. District personnel currently (July 1990) estimate this figure at 90%. Data from this study suggest that at least part of these losses result from not billing farmers for water delivered rather than supplying excess water to farmers (Palmer et al. 1990). This analysis is for number of deliveries and not volume, thus the percentage numbers for conveyance losses and unbilled deliveries cannot be directly related. The district does not compare water order reports with subsequent delivery records and does not compare water supplied to laterals with that billed along the laterals.

The distribution of billed flow rates (Fig. 2) was similar to that of the ordered rates, except that there were relatively more low rates billed than ordered. The mean and median billed rates were 522 and 566 ℓ/s, respectively. Figure 3 shows the distribution of billed durations, which had a mean value of 17.4 hr and a median value of 12.0 hr.

To measure the accuracy of district billing records with respect to deliveries, bill-based adequacy was defined as the ratio of measured flow rates or durations to the corresponding billed quantities: Q_a/Q_b or D_a/D_b (Fig. 8). The mean billed adequacy of flow rate and duration were 1.00 and 1.03, respectively. So on average, the district billed for the correct rate, and for 3% shorter durations than measured by the monitoring equipment.

As Fig. 8 shows however, bill-based adequacy values were widely distributed about the mean, with 43% of the flow rates on bills within 10% of monitored average flow rates and 50% of bill durations within 10% of monitored times. Comparison of bill- and order-based adequacy distributions (Fig. 8 and Fig. 2) indicates that the district was better able to match billed to actual flow rates than to match actual to ordered rates. The order- and bill-based adequacy of flow rate were compared and regression analysis revealed a positive correlation with a r^2 value of 0.20 (Fig. 9). When 'outliers' ($0.6 < Q_a/Q_o < 1.6$) were excluded from the analysis, regression indicated that more than half the variation ($r^2 = 0.54$) in bill-based adequacy of rate could be attributed to the order-based adequacy. The structure of the data (Fig. 9) suggest that when ditchriders decide what rate to bill the farmer, they compromise between the actual and ordered rates.

Billed durations, on the other hand, did not match actual durations as well as the actual durations matched orders. The order- and bill-based flow duration adequacy values were essentially uncorrelated (r^2 of linear regression close to zero).

Discussion

Remarkably, the canal network is operated essentially without a supervisory control system and with very little main canal storage. It was evident from the interviews that the dispatcher, ditchriders and patrolmen exercise a great deal of skill and judgement in moving water from place to place, dealing with unforeseen demand and other unusual situations. Personnel were uniformly proud that the amount of water spilled as operational losses was very small.

It was clear from this study that the district was capable of much better delivery service than was indicated by the official ordering and delivery policy (which hadn't been changed for a long time). Some district personnel we interviewed expressed frustration and stress over the difference between the official and actual ordering policies. They felt it made their job more difficult since the

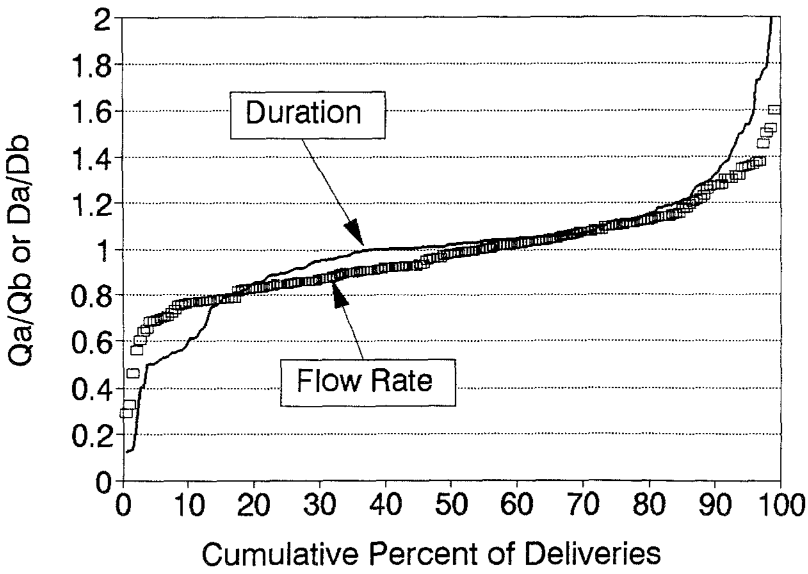

Fig. 8. Distribution of bill-based adequacy of delivered flow rates and durations.

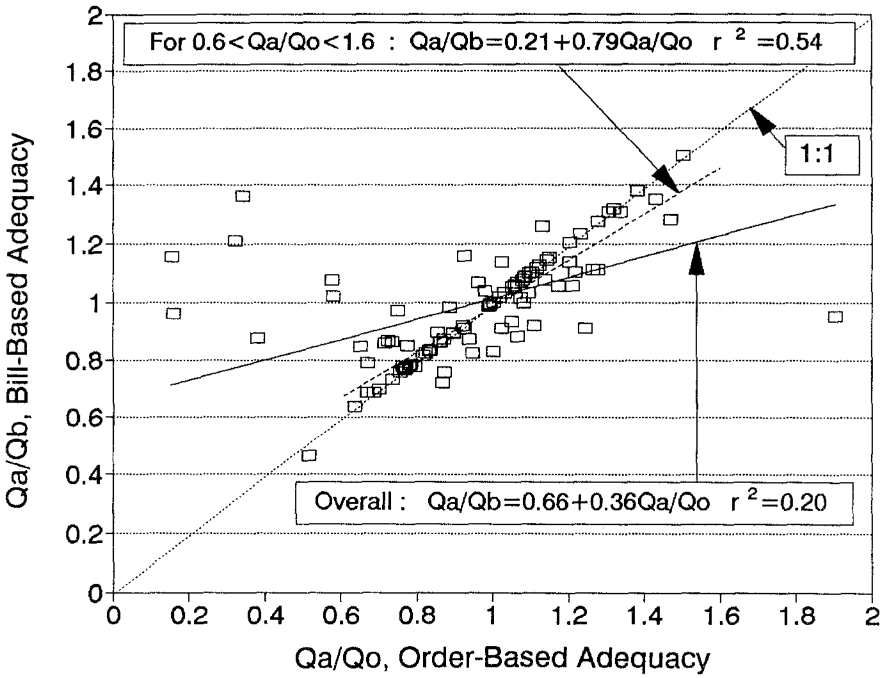

Fig. 9. Comparison of order- and bill-based adequacy of delivered flow rates, with regression results and 1:1 line for reference.

rules were not firmly established. It would probably be appropriate for the district to review their water ordering policies and establish new official policies that are more in line with their capabilities of delivering water. Creating a new policy may or may not be easy for the district to do since they have very little written information on their procedures for providing this service. For example, knowing more about the unofficial requested water would help in understanding the actual lead time the district needs to adequately deliver water.

In many districts, hydrographers measure and record flow rates to the lateral canals. These records can be used to compare the volume of water diverted to the lateral versus that billed to farmers on the lateral. Such records allow the district to identify the cause and location of unaccounted-for water. If the district has an interest in determining the whereabouts of its unaccounted-for water, reinstating the position of hydrographer to make independent flow rate measurements might be considered. More accurate measurement at lateral headings might also improve the ability of ditchriders to set flows accurately. Several ditchriders interviewed indicated that uncertainty about lateral flows caused them to frequently reset lateral heading so that turnout flows would match demands. Wall gauges mounted on monitoring flumes (Bos et al. 1984) in the laterals after the study were well received by the ditchrider.

Ditchriders said in interviews that they typically measure flow only once during a delivery, usually right after delivery has begun. The flow uniformity data show that a given flow measurement during irrigation is likely to be different than the delivery mean. More frequent measurements would probably provide for more accurate estimates of delivered water for an individual event.

The inaccuracies in water measurement and accounting appeared to be random over the area studied. Thus there did not appear to be favoritism to any particular farmers or turnouts. Some differences in ability to get water during the high demand periods were noted, as is commonly reported in other districts. However, these effects appeared to be relatively minor.

It is not known if the unbilled deliveries found were unrecorded spills or unauthorized diversions, or if the record cards were simply lost. District management suggested that the 'unbilled' deliveries identified in this study may have resulted from billing to other turnouts controlled by the same farmer as those at which the deliveries actually occurred. The bills for turnouts within the ditchrider division were searched for events corresponding to measured deliveries, but those further away would have been missed by this analysis.

The authors approached this study from the perspective of water conservation, as indicated by the types of performance measures reported herein. District personnel's primary motivation is service to farmers; that is, providing them with water needed to economically produce crops with a reliable water supply. They work toward the most flexible service at the least possible cost. Water conservation is a secondary consideration. Overall district project water use efficiency exceeds 60% [(diversion-drainage)/diversion]. This assumes that all drainage water pumped resulted from irrigation water diverted to the project. Actual project efficiency is likely higher when considering flood inflows. Thus even with the conditions noted here, project efficiency exceeds that of most irrigation projects in the United States. In addition, the drainage water still carries away more salt than that supplied with the irrigation water, indicating that salt is still being leached from the soil in some parts of the district. The district has a relatively secure (senior water right along the river) and inexpensive water supply and few high water table problems. These factors provide the district with little incentive for additional water conservation efforts.

If the farmers are getting adequate service, adequate water, and the billing errors are randomly distributed, is the cost of better water accounting for the sake of better water accounting justified? The current district operations appear to be compatible with the level of farm water management within the district. It is likely however, that better measurement and accounting might reduce the stress on district personnel, and possibly at nominal cost, and provide improved service to farmers. If water supplies to the district were limited or if drainage were a problem for the district, such improved measurement and accounting could easily be justified.

Summary and conclusions

The performance of the Wellton-Mohawk Irrigation and Drainage District was assessed using information from canal monitoring, district records, and diagnostic analysis interviews. In many cases, actual performance was found to differ from the designed or intended performance, and *de facto* policies were sometimes different from official policies. However, the district has evolved a very flexible system for irrigation water delivery in response to farmers' demand for service. Considering the physical system that exists, the district is doing a good job at delivering water as needed. The two biggest shortfalls observed were the lack of sufficient flow measurements at intermediate points within the district and the lack of good water accounting. These types of problems are not unique to this district, but occur in one form or another in many irrigation districts.

Timeliness and adequacy terms were introduced to measure the accuracy with which district personnel were able to provide the flows ordered by farmers.

It was found that farmers used the official ordering process only about half the time, but more often in the late summer than in the spring. Most deliveries occurred within one day of the date ordered, but tended to be later in the late summer when demand is high. Farmers generally ordered flow rates considerably greater than the designed standard turnout flow, but the delivered rates were usually significantly different (both higher and lower) than ordered. Delivery durations were usually very close to ordered durations. The rates and durations billed to farmers were frequently quite different (both higher and lower) than those measured.

This case study helps to demonstrate the very complex nature of district operations and the relationship between farm and district personnel. The study of system designs and official policies are not sufficient for understanding performance. District operations evolve over time with changes in farm water management needs and the irrigated agricultural environment at large. Assessments such as this can be valuable for engineers designing and upgrading irrigation delivery systems, by helping them to understand the day-to-day decision-making and actions taken to meet district and farm objectives, and the effects of those actions.

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